Trinity River Basin, Texas

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ABSTRACT

In 1991 the Trinity River Basin National Water-Quality Assessment (NAWQA) was among the first 20 study units to begin investigations under full-scale program implementation. The study-unit investigations will include assessments of surface-water and ground-water quality. Initial efforts have focused on identifying water-quality issues in the basin and on the environmental factors underlying those issues. The environmental setting consists of both physical and cultural factors. Physical characteristics described include climate, geology, soils, vegetation, physiography, and hydrology. Cultural characteristics discussed include population distribution, land use and land cover, agricultural practices, water use, and reservoir operations. Major water-quality categories are identified and some of the implications of the environmental factors for water quality are presented.

INTRODUCTION

The protection and enhancement of the quality of the Nation's ground and surface water are among the highest priorities of local, State, and Federal governments. Nationally consistent information on the status and trends in water quality is needed to assess past investments in water-quality management and to provide a base of knowledge for making future decisions. To meet this need, Congress appropriated funds in 1986 for the U.S. Geological Survey (USGS) to test and refine concepts under a National Water-Quality Assessment (NAWQA) Program. After an initial pilot phase, in which methods useful for a full-scale national water-quality assessment program were developed, tested, and refined (Hirsch, Alley, and Wilber, 1988), the Trinity River Basin was selected to be among the first 20 river basins and aquifer systems (referred to as study units) to be investigated under the full-scale implementation plan (Leahy, Rosenshein, and Knopman, 1990).

A major design feature of the NAWQA program is the integration of study-unit investigations as building blocks of future national-synthesis investigations. This approach will provide results useful both in understanding and managing the water resources of the study unit and in answering regional and national-scale questions about water quality. The first national-synthesis topics to be investigated are pesticides, nutrients, and suspended sediment. In support of these investigations, preliminary efforts have included identifying the relevant physical and cultural factors which are believed to influence the spatial and temporal distribution of pesticides, nutrients, and suspended sediment. The study-unit team is developing a regionalization strategy which is a subdivision of the study unit into homogeneous regions based on unique combinations of those factors relevant to water quality at the local study-unit and the national scales. The two main assumptions of regionalization are (1) the water quality of a stream or aquifer at a particular point is a function of the environmental factors of the region upstream or upgradient of that point, and (2) by establishing cause and effect relations between the water quality measured at a point in the stream or in the aquifer and environmental factors of the region upstream or upgradient of that point, one can make inferences about the water quality of ungaged regions having similar environmental factors.

Discussions with local representatives who have responsibility for the management of water resources in the basin have resulted in the contribution of the following questions about water quality in the study unit (Trinity River Basin NAWQA Liaison Committee, oral commun., 1991):

- What are the sources and quantities of non-point source contamination, especially from storm events?
- What are the relative effects of agricultural and urban contaminants on water quality and biological communities?
- What are the effects of point and non-point source loadings on ambient conditions?
- What are the background concentrations of contaminants?
- What are the effects of long-term population and economic growth on water quality?

One major goal of the NAWQA program is to "Identify, describe, and explain the major factors that affect observed water-quality conditions and trends"(Hirsch, Alley, and Wilber, 1988). Implicit in achieving this long-term goal is the establishment of cause and effect relations between natural and human factors and observed water-quality conditions. Within the context of the water-quality questions above, and of the retrospective investigations mentioned earlier, eight categories of water-quality properties and constituents have been identified: major ions, trace elements, suspended sediment, bed sediment, nutrients, dissolved oxygen and biochemical oxygen demand, synthetic organic compounds, and biota. The purpose of this article is to present the environmental setting and its overall implications for these water-quality properties and constituents in the Trinity River Basin. This report does not attempt to establish cause and effect relations or to present any detailed analysis of existing data.

Acknowledgments

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ENVIRONMENTAL SETTING

The environmental setting can be described as the total of the many individual physical factors, hydrologic processes, and human influences operating within the study unit. Physical factors affecting water quality in the Trinity River Basin include location and extent, climate, geology, soils, vegetation, physiography, and hydrology. The location of the study unit on the earth controls overall climatic characteristics and the extent or size of the basin will influence water-quality characteristics because of the integrating effect of the stream traveling over the length of the basin traversing areas with diverse environmental factors. Climatic factors such as precipitation and temperature are evident mostly in seasonal changes in water quality and in changes related to stream discharge. The rocks comprising the study unit is the main contributor of major ions, where man’s influence is minimal. Soil, a product of the interaction of climate, geology, hydrology, and vegetation, can affect water quality in several ways. The sediment load of a stream is affected directly by the erodibility of different soils, and soil characteristics can affect the behavior of other water-quality properties and constituents. Climate and soils determine what types of vegetation will grow in an area, and the ability of the land to support agriculture greatly influences land-use practices. Physiography directly affects water quality because it provides physical controls of slope and aspect over runoff processes, and of land-surface altitude over channel geometry. Hydrologic processes or factors operating in the basin include the configuration and extent of the stream network, streamflow variability, and the properties of major and minor aquifers.

Examples of human influences operating in the basin are the discharge of wastewater, construction and operation of reservoirs, development and expansion of urban areas, energy production, livestock operations, cultivated farms, and silviculture. Population growth and distribution data for the study unit, as well as the appropriate land-use and land-cover classes, can be used as surrogate variables in exploratory data analysis when designing a sampling network. For example, when conducting an investigation of the relation between nitrates in ground water and the application of agricultural fertilizers, knowledge of the amount and location of fertilizer application is necessary but is often difficult to obtain. A land-use classification identifying cropland in the study unit when used together with standard fertilizer application rates for crops typically grown on the cropland, would allow some initial statistical testing of hypotheses related to the occurrence or nonoccurrence of nitrate values in ground water underlying the cropland. In this way, a sampling network may be designed which would concentrate study resources in only those areas likely to contribute nitrates to ground water.

Location and Extent

The Trinity River Basin NAWQA study unit is located in the south-central United States, in east-central Texas, with the northernmost part at approximately latitude 33o45’ N. and longitude 97o45’ W. (fig. 1). It extends on a southeast diagonal, from immediately south of the Oklahoma-Texas State boundary to the Trinity Bay at the Gulf of Mexico, approximately latitude 29o45’ N. and longitude 94o45’ W., a distance of about 360 miles (mi). The study-unit boundary is defined as the surface-water drainage divide of the Trinity River, except in the area near the coast where it is comprised of sections of the Chambers County boundary, and part of the western boundary of Liberty County. The study unit includes about 18,570 square miles (mi2) or about 7 percent of the total area of the State of Texas (267,300 mi2), with 38 Texas counties at least partially within the study-unit.

FIGURE 1.--Location of the Trinity River Basin study unit and major cities..

Climate

The climate of the study unit can be described as modified-marine, subtropical-humid, having warm summers and a predominant onshore flow of tropical maritime air from the Gulf of Mexico. The onshore flow is modified by intermittent seasonal intrusions of continental air and exhibits an east to west decrease in moisture. This is attributed to changes in land elevation over the basin from east to west, and its proximity to the Gulf of Mexico and the southern Great Plains (Carr, 1967).

Average annual precipitation ranges from less than 36 inches (in.) in the northwest part of the study unit to greater than 52 in. in the southeast (fig. 2A). On average, the study unit experiences a winter surplus and a summer deficiency of precipitation, as compared to potential evapotranspiration. Average annual temperature is fairly uniform throughout the basin, ranging from about 69 oF in the southeastern area of the study unit to about 65 oF in the northwest (fig. 2B). Average annual runoff ranges from less than 4 in. in the northwestern project area to greater than 16 in. in the southeast (fig. 2C). Average annual recharge plus evapotranspiration ranges from less than 30 in. in the northwest to greater than 40 in. in the southeast (fig. 2D). There is a general increase in average runoff from west to east that coincides with the increase in average annual precipitation. The period 1951-80, is being used by climatologists to represent current averages in precipitation, temperature, runoff, and recharge plus evapotranspiration, as well as lake evaporation over the study unit (Larkin and Bomar, 1983).

FIGURE 2.--Average annual (A) precipitation, (B) temperature, (C) runoff, and (D) recharge plus evapotranspiration.

Geology

Surficial geology of the study unit, shown on figure 3A, illustrates some of the results of the various depositional phases which have occurred through geologic time; there are deposits ranging in age from Pennsylvanian to Quaternary (Godfrey, McKee, and Oakes, 1973). These geologic strata are continually acted upon by structural forces (fig. 3B), and, with differing rates of erosion and deposition define, to a large extent, the physiographically-distinct areas of the study unit (Hill, 1901).

FIGURE 3.--(A) surficial geology, (B) structural geology, (C) physiographic provinces,

and (D) ecoregions.

During the early Paleozoic Era, approximately 600 to 350 million years ago, shallow seas inundated most of the central Texas region, and a marine and near-shore sand, shale, and limestone sequence was formed. During the Pennsylvanian Period, approximately 320 to 245 million years ago, sedimentary rocks of the late Paleozoic Era were deposited in the most northwestern part of the study unit. Paleozoic rocks underlie about 6 percent of the study unit.

Approximately 245 to 200 million years ago, the European and African-South American tectonic plates began to separate from the North American plate and a series of rift basins were formed. By the Cretaceous Period, approximately 150 to 70 million years ago, shallow seas had invaded much of what is present-day Texas. This allowed near-shore sand and marine shale and limestone to be deposited across most of the study unit. The Cretaceous Period closed with uplifting of the area and subsidence of the Coastal Plain and Gulf of Mexico areas. Cretaceous formations crop out in about 48 percent of the study unit.

Following the Cretaceous Period, approximately 70 million years ago, Tertiary and Quaternary sediments were deposited on the subsiding Cretaceous rocks, and an alternating sequence of marine and continental formations was created as a result of repeated transgression and regression of the sea. The marine sediments are characterized by clay, shale, and marl, with minor amounts of sand. Continental and near-shore deposits consist primarily of sand, with lesser amounts of clay, shale, and lignite. Tertiary formations underlie about 30 percent of the study unit and Quaternary sediments underlie the remaining 16 percent of the study unit.

Physiography

The Trinity River Basin study unit is a modified sedimentary landform, reflecting its depositional geologic history (Hill, 1901). The study unit is dissected by alternate bands of rolling, treeless prairies, smooth to slightly rolling prairies, rolling timbered hills, and a relatively flat coastal plain. The study area slopes gradually from about 1,200 feet (ft) above sea level in the northwest, to about 600 ft, mid-basin, and on to sea level in the southeastern section of the area, at Trinity Bay. Land-surface altitude decreases at about 2.7 feet per mile (ft/mi) over the length of the study unit.

Several formal physiographic classifications can be used to group various characteristics of the land surface. These classes provide a hierarchical subdivision of the land surface which tends to be most useful for the application for which it was designed, but often can be applied in other areas.   For instance, one classification, developed for the entire conterminous United States, is the "Physical Divisions of the United States" (Fenneman and Johnson, 1930). This classification provides the most general subdivision of the study unit, and has broad application in hydrology as it provides the scientist with an initial description of the regional characteristics of a particular study area. As can be seen in figure 3C, the Trinity River study unit is located almost entirely in the Coastal Plain Province, West Gulf Coastal Plain Section. Fenneman and Johnson described this area as a "young grading inland to mature coastal plain." The extreme northwestern part of the basin is located in the Central Lowlands Province, Osage Plains Section, with a minor part in the Great Plains Province, Central Texas Section. The Osage Plains Section of the Central Lowlands Province is an area where the limestone cover of the Edwards Plateau (Lower Cretaceous) has been completely eroded, exposing the level surface of the underlying rocks (Fenneman, 1931).

Omernik and Gallant (1987) have mapped ecoregions for the United States which identify areas of relatively homogeneous ecological makeup. These areas have their basis in land-surface form, potential natural vegetation, soils, and land-use and land-cover pattern. The five ecoregions coincident with the Trinity River NAWQA study unit are shown on figure 3D.

Land Resource Areas (LRA) in Texas (Godfrey, McKee, and Oakes, 1973), are recognized as areas distinct in topography, soils, and vegetation. They subdivide the State and provide a more detailed classification than the broad physiographic provinces developed by Fenneman (1931).

The Land Resource Unit (LRU) (Kier, Garner, and Brown, 1977) is a classification based on distinctions in topography, geology, and vegetation, but additionally provides a qualitative characterization and assessment of the suitability of the land for various types of activities. This can provide insight on current land-use practices, land potential, or both.

At this time the study-unit team has adapted the term Integrated Land Resource Unit (ILRU) from a combination of the above classification systems. The name of each ILRU is identical to the Land Resource Area, but each ILRU contains characteristics or attributes derived from the LRA maps, the LRU maps, Fenneman’s physical divisions, and Omernik and Gallant’s ecoregions. This provides a useful framework for comparing and contrasting those environmental factors, or combinations of environmental factors which may affect water quality, but equally important, for aggregating local study-unit region findings into potential national-synthesis regions, which may be based on a broader, more regional classification system such as Omernik and Gallant's ecoregions. Figure 4 is a chart that shows the relation of each ILRU to the major environmental factors. The study unit includes 10 ILRUs which are described briefly below, with their locations shown on figure 5.

FIGURE 4.--Integrated Land Resource Units (ILRU) and major environmental factors.

FIGURE 5.--Integrated Land Resource Units (ILRU).

The North Central Prairie ILRU makes up 1,179 mi2 or about 6 percent of the study unit, and is underlain primarily by Pennsylvanian sandstone, shale, and limestone. The soils are undulating to hilly alfisols soils over shale or sandstone and nearly level soils of coarse sand in the outwash areas, moderately deep to deep, non-calcareous, with loamy surface layers, and clayey subsoils (Godfrey, McKee, and Oakes, 1973). The area is level to hilly with potential natural vegetation types of oak/hickory, and bluestem prairie grass. Cultivated land is locally important, but the majority of the area is rangeland. The outcrop of rocks of the Lower Cretaceous Period is the boundary separating the North Central Prairie ILRU from the Western Cross Timbers ILRU (Hill, 1901).

The Western Cross Timbers ILRU makes up 1,250 mi2 or about 7 percent of the study unit. The area consists of alfisol soils, sandy or clayey, mostly acidic, formed from sediments derived from Lower Cretaceous Period (Comanche Series) sandstones and shales (Godfrey, McKee, and Oakes, 1973). The relief is generally level to undulating with potential natural vegetation types of oak/hickory, and bluestem prairie grass. Land use and land cover is residential or urban with pasture, crops, some woodlands, and rangeland. Fruit and vegetable crops are grown extensively in the most southern areas. Crops grown include peanuts, grain, sorghums, small grains, peaches, pecans, and vegetables.

The Grand Prairie ILRU makes up 1,836 mi2 or about 10 percent of the study unit. It is an area distinct from and separating the Eastern and Western Cross Timbers areas. The area is most readily distinquished by the level to hilly prairie which is devoid of trees except near streams with potential natural vegetation types of oak/hickory, and bluestem prairie grass. Lower Cretaceous limestone-based mollisol soils, moderately alkaline, mostly calcareous, have been adapted to raising livestock and to growing corn, small grains, and sorghum (Godfrey, McKee, and Oakes, 1973).

The Eastern Cross Timbers ILRU is an area which makes up about 985 mi2 or 5 percent of the study unit. The area consists of rolling plains with potential natural vegetation types of oak/hickory, and bluestem prairie grass. Alfisol soils, sandy or clayey, mostly acidic, formed from sediments derived from Upper Cretaceous Period sandstones and shales are dominant in the area. Land use is residential or urban and agricultural with pastures, crops, some woodlands, and rangeland. Crops grown are peanuts, sorghums, small grains, peaches, pecans, and vegetables.

The Blackland Prairie ILRU makes up 4,939 mi2 or about 27 percent of the study unit and is characterized by undulating to nearly level relief, varying in width from 20 to 70 mi within the study unit. It is located in the center of the study unit and is very important agriculturally to the State. Most of the area has been cultivated and only small remnants of the original prairie grasslands exist today. During the 1930s, this area was the principal cotton producing area in Texas. Vertisols soils were derived from alkaline, calcareous marine sediments of Upper

Cretaceous Period (Gulf Series), and have a high shrink/swell potential as well as a high corrosion potential. Land use is mainly agricultural, with cropland and pasture, and some urban area. Predominant vegetation is cropland with minor areas of tall grass, elm and hackberry woods. The main crops are grain sorghum, wheat, cotton, corn, and hay. Pasture is used for beef and dairy cattle.

The Texas Claypan ILRU makes up about 2,400 mi2 or 13 percent of the study unit. It is characterized by its level to undulating relief and alfisol soils which originate from Tertiary sediments and have high shrink/swell and corrosion potential. This area is also known as the Post Oak Belt or Savannah, because of the post and blackjack oak areas, but elm, walnut, and pecans can also be found along streams. The principal industry is diversified farming and livestock raising. This area has lignite, commercial clays and some other minerals. Scattered areas are used for pasture or cool-season forage crops.

The Eastern Timberlands ILRU makes up about 2,124 mi2 or 11 percent of the study unit. The area is underlain by acidic alfisol, utisol, and mollisol soils originating from Tertiary sediments (Godfrey, McKee, and Oakes, 1973). Relief is undulating with rolling plains and some rolling hills. Mixed pine and hardwood forest are the native vegetation, interspersed with native and improved grasslands. This area is the principal commercial timber area of the State.

The Coastal Prairie ILRU makes up about 861 mi2 or 5 percent of the study unit. It is located in the southern part of the study unit and has level to gently undulating relief. It is underlain by a mollisol and vertisol mixed soil, derived from Quaternary age sediments. This soil is strongly acidic to moderately alkaline, has a high sodium content in the lower layers, and presents high shrink/swell potential and corrosion potential (Godfrey, McKee, and Oakes, 1973). Tall grass along streams make up the native vegetation, as well as cord grass and other bunch grasses and sedge. There are some pine forest areas. Grain sorghum, cotton, and soybeans are grown in this area and a dense cattle population exists. Ranching is the principal agricultural activity.

The Coastal Marsh ILRU makes up about 107 mi2 or 1 percent of the study unit. It is located in the most southerly part of the study unit and is level with clay to sand mollisol soils and has cord and other sedge grasses. These are wet lowlands suited mainly to raising cattle on the salt-tolerant marsh grasses.

The Bottomlands ILRU makes up about 2,886 mi2 or 15 percent of the study unit. The area consists mainly of Quaternary age alluvial sediments deposited over the flood plain of the Trinity River and its tributaries. The soils are alkaline to acidic, supporting water oaks and elm and shade tolerant grasses. The soils have high shrink/swell and corrosion potential and are subject to flooding. Currently, land use and land cover consists of cropland, wetlands, and forest.

Ground-Water Hydrology

Aquifers in Texas have been classified as major or minor (fig. 6) based on their abilities to supply ground water (Texas Board of Water Engineers, 1958). Using that classification, there are three major aquifers in the Trinity River Basin, the Trinity Group, Carrizo-Wilcox, and Gulf Coast, and three minor aquifers in the basin including the Woodbine, Queen City, and Sparta. There are many other water-bearing formations which yield small or moderate quantities of water and may be important locally. Properties of major and minor aquifers in the Trinity River Basin are summarized below. More detailed descriptions of ground water in the Trinity River Basin are found in Peckham and others (1963), Muller and Price (1979), Nordstrom (1982), Texas Department of Water Resources (1984), and Baker and others (1990). Several reports have summarized the U.S. Geological Survey Gulf Coast Regional Aquifer-Systems Analysis (RASA) study and include the lower half of the Trinity River Basin. Hosman and Weiss (1991) described in detail the geohydrologic framework for the Texas coastal uplands aquifer system. Pettijohn, Weiss, and Williamson (1988) presented maps of dissolved-solids concentrations for the Gulf Coast aquifer systems. Ryder (1988) described the hydrogeology and predevelopment flow in the Texas Gulf Coast aquifer system.

FIGURE 6.--Major and minor aquifer outcrop areas.

The Trinity Group aquifer includes the Travis Peak, Glen Rose, and Paluxy Formations (Peckham and others, 1963; Muller and Price, 1979). The water-bearing zones consist mostly of fine-grained quartz sand in lenses or layers which, individually, are as much as 50 ft thick. Clay and shale lenses interfinger with the sand lenses, and gradations from sand to clay occur laterally and vertically. Total thickness of the aquifer ranges from less than 100 to about 1,200 ft. The Trinity Group aquifer crops out in the northwest part of the Trinity River Basin (fig. 6) and dips to the east-southeast from about 30 ft/mi in the outcrop to about 70 ft/mi downdip (Peckham and others, 1963). Yields of large-capacity wells average about 430 gallons per minute (gal/min), with wells in some areas yielding more than 2,000 gal/min (Texas Department of Water Resources, 1984). Recharge to the aquifer is primarily in the outcrop and the discharge is to wells, overlying beds, and the downdip saline zone. Historically, the water moved in the direction of the aquifer’s dip; however, major cones of depression have formed in Tarrant and Dallas Counties where water levels have declined from near land surface to several hundred feet below land surface (Baker and others, 1990).

The Carrizo-Wilcox aquifer includes the Wilcox Group and the Carrizo Formation of the Claiborne Group. The underlying Wilcox consists of interbedded sand, sandstone, sandy shale, shale and lignite. The Carrizo is a white to gray, well-sorted, sand or poorly cemented sandstone. Thickness of the Carrizo-Wilcox ranges from less than 100 to more than 2,500 ft, with about 50 percent of the thickness being sand (Peckham and others, 1963). Yields of large-capacity wells average about 420 gal/min, and maximum yields are more than 1,000 gal/min (Texas Department of Water Resources, 1984). In the general area of the outcrop, the aquifer dips to the southeast at 20 to 25 ft/mi. Southeast of the outcrop, structural highs and faults disrupt the trends. Immediately south of this disrupted area, the angle of dip increases with distance downdip, from about 50 ft/mi to more than 100 ft/mi at the limit of the freshwater zone. The uniformity of the aquifer is disrupted by salt domes in several locations. Water levels vary from near the land surface to 500 ft below land surface in hilly areas and in cones of depression centering around well fields. Primarily, the aquifer recharges in the outcrop and discharges to wells, overlying beds, and the saline zone. Water moves in the general direction of the aquifer dip, except where major cones of depression have developed (Peckham and others, 1963).

The Gulf Coast aquifer is composed of seven stratigraphic units which crop out over much of the lower Trinity River Basin. These include the Catahoula, Oakville, Lagarto, Goliad, Willis, Lissie, and Beaumont Formations, as well as overlying surficial deposits of alluvium. The aquifer consists of alternating beds of clay, silt, sand, and gravel which are hydrologically connected and form a large, leaky artesian-aquifer system. The principal water-bearing units are the Goliad, Willis, and Lissie Formations. This system reaches a maximum thickness of about 3,500 ft, of which about 40 percent is water-bearing sand (Peckham and others, 1963). Yields of large-capacity wells average 1,500 gal/min, but locally wells produce up to 3,400 gal/min (Texas Department of Water Resources, 1984). Recharge is mostly in the outcrops of the individual formations. Water moves downdip within the formations, and discharge is to wells, to the downdip saline zone, and vertically to adjacent formations. Withdrawals of ground water by wells have resulted in local and regional cones of depression centering in the Houston area and land subsidence (fig. 1). As a result of the large withdrawals, upward vertical gradients have been reversed in those areas. Some water also is derived from the reduction in storage associated with compaction of clays (Muller and Price, 1979).

The Woodbine aquifer (fig. 6) is composed of lenticular, crossbedded, loose to slightly consolidated, fine-grained sand and sandstone that is interbedded with clay. Sand beds make up about 50 percent of the aquifer and are more common near the base of the aquifer. The aquifer is exposed at the surface in a narrow belt from southeastern Cooke County to Johnson County. The Woodbine aquifer dips eastward into the subsurface of northeast Texas where it reaches a maximum thickness of about 700 ft near the downdip limit of fresh to slightly saline water (Nordstrom, 1982). The dip ranges from 35 ft/mi in the outcrop area to 100 ft/mi at the downdip limits (Peckham and others, 1963). Yields of large-capacity wells average 130 gal/min, but locally wells produce as much as 600 gal/min (Texas Department of Water Resources, 1984). Muller and Price (1979) estimated that about 1 in. of average annual recharge in the outcrop area was necessary to satisfy withdrawals. However, wells operating under artesian conditions have experienced declines in water levels of up to 10 ft/yr with the greatest declines in the area of Grayson County (Nordstrom, 1982)

The Queen City aquifer consists chiefly of crossbedded, medium- to very fine-grained sand. The sand beds are massive to thin and interbedded with lenses of shale and sandy shale. Lignite is present in some locations. The aquifer ranges from near zero to more than 500 ft in thickness, with 60 to 70 percent being sand. The aquifer is exposed at the surface throughout much of its extent in northeast Texas and dips 50 to 60 ft/mi toward the southeast beneath younger formations (Peckham and others, 1963). Yields of wells are generally small, only a few exceed 400 gal/min, and most are less than 250 gal/min (Texas Department of Water Resources, 1984). Water levels range from near land surface in the outcrop to more than 200 ft below the land surface in southwest Anderson County. Recharge is mostly from rainfall in the outcrop; discharge is to wells, adjacent aquifers, and the saline zone (Peckham and others, 1963).

The Sparta aquifer is composed mainly of medium-grained sands and interbedded clays. Sand makes up 60 to 70 percent of the total thickness, which ranges from 100 to approximately 300 ft. The Sparta crops out in southern Leon and northern Houston Counties (fig. 6). Immediately downdip from the outcrop, the aquifer dips toward the southeast at a rate of about 50 ft/mi. The angle of dip increases to as much as 150 ft/mi in southern Houston and northern Trinity Counties (Peckham and others, 1963). Large-capacity wells, producing principally from thick sand beds near the base of the formation, generally yield 400 to 500 gal/min, but locally wells produce up to a maximum of 1,200 gal/min (Muller and Price, 1979). Water levels range from land surface to almost 200 ft below land surface. Muller and Price (1979) estimated that approximately 5 percent of the average annual precipitation received on the outcrop as effective recharge can be transmitted downdip by the aquifer for development. Some of the ground water is discharged by springs and seeps, and by evapotranspiration in the outcrop. Discharge is to wells, to the saline zone down dip, and to overlying beds (Peckham and others, 1963).

Surface-Water Hydrology

The headwaters of the Trinity River (fig. 7) are in the North Central Prairie ILRU in the northwest and the Eastern and Western Cross Timbers, Grand Prairie, and Blackland Prairie ILRUs in the north and northeast. The western part of the basin is drained by the Clear Fork Trinity River and the West Fork Trinity River, which join in Fort Worth (fig. 1). The north-central part of the basin is drained by the Elm Fork Trinity River. The Elm Fork Trinity River joins the West Fork Trinity River in Dallas to form the Trinity River. The northeast part of the basin is drained by the East Fork Trinity River which joins the Trinity River about 20 mi southeast of Dallas. The central basin is drained by two tributaries, Cedar Creek from the east and Richland Creek from the west. Both tributaries are in the Blackland Prairie ILRU with small parts of each in the Eastern Timberlands. The southern basin, downstream from the mouth of Richland Creek, narrows to a width of about 45 mi. Tributaries in this section of the basin generally are small, draining the Texas Claypan ILRU from the west, the Eastern Timberlands from the east, and the Coastal Prairie in the south.

FIGURE 7.--Stream network, major reservoirs, and selected streamflow gaging stations.

Total flow out of the Trinity River Basin can be approximated from flow measured at station 08066500, Trinity River at Romayor, Texas. The drainage area at station 08066500 is 17,186 mi2 or about 93 percent of the Trinity River Basin study unit. Average discharge from 1924-90 was 7,340 cubic feet per second (ft3/s) or 5,320,000 acre-feet per year (acre-ft/yr). The largest flows in the Trinity River, as indicated by 6 years of daily flows at station 08066500 (fig. 8), occur during winter and spring. Summer flows are highly variable and the smallest flows occur during summer and early fall.

FIGURE 8.--Daily discharge at station 08066500, Trinity River at Romayor, Texas.

The natural stream network has been extensively modified by man. Numerous reservoirs have been built to retain runoff on all major tributaries and the mainstem of the Trinity River, and diversions move water within the basin and to and from adjacent river basins. Total outflow from the major urban wastewater-treatment plants (WWTP's) increased from less than 200 million gallons per day (Mgal/d) in 1970 to about 600 Mgal/d in 1990 (Sam Brush, North Central Texas Council of Governments, written commun., 1992). The largest interbasin diversion is out of the basin, from the Trinity River below Livingston Reservoir to the Houston metropolitan area. In 1989, 260,000 acre-ft were diverted out of the basin, equal to 4.9 percent of the mean annual discharge at station 08066500. There are numerous other inter and intrabasin diversions. Sources of municipal water for Dallas and Fort Worth (some of which is returned to the river as effluent) include reservoirs on Chambers Creek, Richland Creek, Cedar Creek, Clear Fork Trinity River, Elm Fork Trinity River, East Fork Trinity River, and the neighboring Sabine River east of the study unit.

Medium and large reservoirs (greater than 10,000 acre-ft capacity) are shown on figure 7. In addition to those 22 reservoirs, there are about 1,000 smaller reservoirs in the basin. Most of these are floodwater-retarding structures, constructed by the Soil Conservation Service (U.S. Department of Agriculture, 1979), with capacities generally between 500 to 1,000 acre-ft.

Reservoir storage capacity can be reported in two ways, conservation capacity and available capacity. Conservation capacity is the volume of water in a reservoir at the normal maximum operating water level. Available capacity is the maximum volume of water that can be withdrawn from a reservoir each year, on a dependable basis, during a repetition of the most critical drought of record or the volume that could be developed under the operating mode of the supply source during drought conditions. Reservoir conservation capacities for the 22 medium and large reservoirs in the Trinity River Basin are listed in table 1. Total conservation capacity in the basin, including the capacities of the small reservoirs and floodwater-retarding structures not listed in table 1, is estimated to be about 7,500,000 acre-ft, or about 1.4 times the mean-annual flow at station 08066500.

TABLE 1.--Major reservoirs in the Trinity River Basin study unit

Eleven USGS streamflow gaging stations were used to characterize the magnitude and variability of flow in the Trinity River Basin (table 2). These stations were selected because they had long-term daily discharge records and because they are at locations affected by the major natural and human factors. The locations include: (1) four stations gaging relatively undisturbed watersheds, (2) four stations downstream from large return flows (point-sources) in the Dallas-Fort Worth metroplex, and (3) three stations directly downstream from reservoirs.

TABLE 2.--Spearman's rank correlations on the mean, standard deviation, and skew for daily streamflow over time at eleven streamflow gaging stations.

Two methods were used to analyze the magnitude and variability of flow. The first was to plot the frequency distribution of daily discharge values for selected periods of record, often referred to as a flow-duration curve. A flow-duration curve shows the percent of time that flow exceeds a given rate and thus provides information on the magnitude and variability of flow. If conditions change upstream from a station (for example, a reservoir is constructed) then flow-duration curves determined from time periods before and after that change will probably be different. The second method of analysis was to use Spearman's rank correlations (Iman and Conover, 1983) to evaluate long-term trends, or lack of trends, in the mean, standard deviation, and skew calculated for 5-year periods of daily discharge values. Means of 5-year periods were evaluated to determine if trends existed in average or total discharge. Standard deviations were evaluated to determine if there were trends in the variability of flow with time; standard deviation is the square root of variance. Skew was evaluated to determine if there were trends in the normality of flow distribution with time. If skew decreased with time, then flows at that station might be approaching a normal distribution for successive 5-year periods.

Four of the 11 stations are located in areas that are relatively undisturbed: station 08042800, West Fork Trinity River near Jacksboro, Texas; station 08044000, Big Sandy Creek near Bridgeport, Texas; station 08053500, Denton Creek near Justin, Texas; and station 08066170, Kickapoo Creek near Onalaska, Texas. Flow-duration curves for three selected 10-year periods at station 08042800 (fig. 9) are similar. Flow-duration curves at the other three relatively undisturbed stations also did not change with time. With one exception, statistics for 5-year groups of daily flows for these stations show no significant changes with time (at the 90 percent confidence level; table 2). The exception was mean flow at station 08066170 where mean flow for the 5-year periods increased. That increase probably reflects the period of record at this site, which began in 1950, closely preceding the drought of the 1950's. Other sites indicate that the magnitude and variability of runoff in relatively undisturbed areas in the Trinity River Basin has not changed significantly during the period of record. Drainage areas for the four stations are relatively small (less-than 700 mi2) and the streams are ephemeral. Station 08044000 has a reservoir upstream from it (closed in 1956) that captures flow from 30 percent of the 333-mi2 drainage area upstream. An additional 14 percent of the drainage area is controlled by 19 flood-water retarding structures; however, these reservoirs have not caused statistically significant changes in the magnitude or variability of flow.

Low flows increased with time in the West Fork Trinity River and the Trinity River, in and downstream from Fort Worth and Dallas, as illustrated by flow-duration curves for three 10-year periods at station 08062500, Trinity River near Rosser, Texas (fig. 9). Effluent discharge from regional wastewater treatment plants has increased from about 280 Mgal/d in 1970 to about 550 Mgal/d in 1990, resulting in increased base flow in the river (Brush and Promise, 1990). From 1903 to 1907 at station 08057000, Trinity River at Dallas, Texas, flow was less than about 2.0 ft3/s 10 percent of the time. By 1983-87, 80 years later, flow at that station was never below about 200 ft3/s. Some of the increase in base flow could be caused by discharges from upstream reservoirs; however, the major cause of that increase was increased discharges of wastewater effluent from the metroplex.

FIGURE 9.--Flow duration curves for selected periods at four streamflow gaging stations.

Another change in streamflow downstream from Fort Worth, indicated at three of the four stations below return flows, is the decrease in peak flows with time (fig. 9). The general pattern in flow-duration curves when low flow is increasing and peak flow is decreasing is a counter-clockwise rotation between subsequent curves, for example, curves for station 08062500 (fig. 9). That rotation indicates a smaller range in flow and less variance. There are no statistically significant trends in mean flows computed for 5-year periods for the four stations below return flows; however, there are statistically significant decreasing trends in variance for three stations and skew for two stations (table 2). Decreases in peak flows probably result from attenuation of flood peaks by the numerous reservoirs on tributaries in and upstream from the metroplex.

Urbanization can affect peak flows in the watershed. Urban development is characterized by an increase in impervious cover when buildings are constructed and roads and parking lots are paved. The increase in impervious area typically results in faster runoff of precipitation causing larger peak flows in streams. Land and others (1982) found a 180-percent increase in peak discharge for a flood with a 5-year recurrence interval for streams in the metroplex area following a land-use change from rural to urban.

Flow was analyzed for three stations with extensive records before and after reservoirs capturing runoff from most of their watersheds were closed: station 08055500, Elm Fork Trinity River near Carrollton,Texas; station 08047500, Clear Fork Trinity River at Fort Worth, Texas; and station 08066500, Trinity River at Romayor, Texas. Records at station 08055500 extend back to 1907. Two reservoirs capture runoff from 96 percent of the drainage area to station 08055500: Grapevine Lake since 1952 and Lewisville Lake since 1954. Records at station 08047500 extend from 1924. Benbrook Lake has captured runoff from 83 percent of the Clear Fork drainage at the station since 1952. The third station, 08066500, is 35 mi downstream from Livingston Reservoir. Livingston Reservoir captures runoff from 96 percent of the 17,186 mi2 drainage area upstream of this station, is the largest reservoir in the basin, and the only reservoir on the mainstem below the Dallas-Fort Worth metroplex.

The effect a reservoir has on downstream flow varies depending on the design and operation of the reservoir and on the relation between available storage in the reservoir and inflow. Most of the large reservoirs in the Trinity River Basin were constructed for water supply. Reservoirs used for water supply are kept nearly full to maximize supply, which minimizes available storage during a flood event. Some of the major reservoirs, including Lewisville, Benbrook, Lavon, Navarro Mills, Livingston, and Bardwell, also are used for flood control. For a reservoir to be effective for flood control, storage equal to a significant part of the flood must be available.

Reservoirs also can reduce the flow in a stream by increasing infiltration and evaporation losses. Gilbert and Sauer (1969) estimated that development of a planned system of 162 floodwater-retarding structures controlling 26 percent of the drainage to Lewisville Lake would reduce annual yield to the reservoir by as much as 10 percent. As floodwater-retarding structures filled with sediment, the depletion of annual yield would decline.

After 1954 when Lewisville Dam closed, flood peaks were smaller downstream, as indicated by flow-duration curves for station 08055500, because some floodwaters are retained behind the dam and released gradually (fig. 9). Low flows also are affected by the reservoir operations at this station (fig. 9). The city of Dallas diverts water from the pool at the station and from the river 14 mi. downstream from the station. To provide water for those diversions, streamflow is maintained by reservoir releases during dry periods. The combination of smaller flood peaks and supplemented low flows result in smaller variance in flows as indicated by standard deviation and skew calculated for 5-year groups of daily values (table 2). Mean flow did not change significantly.

Similar changes in the variability of flow are observed for station 08047500 (table 2). Flow at this station is regulated largely by Benbrook Lake. The city of Fort Worth diverts water from the pool at the station in some years and the Benbrook Water and Sewage Authority diverts water from the river upstream of the station. Low flow is supplemented during dry periods by reservoir releases and flood peaks are attenuated, as indicated by changes in flow-duration curves from before and after the reservoir closed in 1952. Mean flow at station 08066500 has not changed significantly since the 1920's (table 2). As with the other mainstem stations below the metroplex, there is clear indication from flow-duration curves that low flows have increased over time. There is some indication that standard deviation and skew have decreased; however, the trends in standard deviation and skew are not statistically significant (table 2). Livingston Reservoir does not appear to have strongly affected the variability of flow at the station since its closure in 1969.

Population and Economic Activities

Texas, with a 1990 population of almost 17 million (A.H. Belo Corp., 1991), is the seventh fastest growing state in the United States, and the third largest in total population behind California (30 million) and New York (18 million). The study unit contains two of the most populous counties in the State, Dallas and Tarrant, which, when combined, had a 1990 population of about 3.0 million, or about 19 percent of the State's total population. Since the 1940's Dallas and Tarrant Counties have increased their proportion of the total population in the basin (fig. 10A). In 1990, these two counties accounted for about 66 percent of the total population of the study unit of 4.5 million. During 1980 to 1990, Dallas and Tarrant Counties showed the second and third largest population increases within the State. Denton County had the largest percent increase of all counties in the State (91 percent) during the same period, followed by Collin County (86 percent), and Rockwall County (76 percent). Also, during this period, the total population in Texas increased by about 19 percent, but the population of the study unit increased by about 26 percent, indicating that the study unit continues to be one of the major growth areas in the State. Population density of the study unit is about 259 persons per square mile, as compared the overall State population density of 67 persons per square mile. Dallas and Tarrant Counties have population densities greater than 1,000 persons per square mile (fig. 10B). Figure 10C shows that basin population mainly is clustered in the Dallas-Fort Worth Metroplex, with a few secondary population clusters.

FIGURE 10.--Trinity River Basin study unit (A) population, 1850-1990, (B) population density, and (C) 1990 population distribution.

The population of the Consolidated Metropolitan Statistical Area (CMSA) covering the Dallas-Fort Worth Metroplex was about 3.75 million people in 1990. The urban and suburban areas include about 65 percent of Dallas County, 50 percent of Tarrant County, and limited parts of Denton and Collin Counties. The area is approximately 1,500 mi2 and represents about 8 percent of the Trinity River Basin study unit. A diverse economic base exists for the Dallas-Fort Worth Metroplex. The major manufacturing industries include automotive, aerospace, electronics, plastics, and oil-field equipment. Large service industries include finance, insurance, and transportation, including the Nation's largest airport.

There are four other cities in the study unit with populations of about 20,000 or more. Denton, population of about 70,000, has two universities, a variety of light manufacturing concerns, and a service sector. McKinney, population of about 25,000, is a local agricultural business and trading center. Corsicana, population of about 25,000, is an agribusiness center, a center for oil-field operations, and has light manufacturing and service industries. Waxahachie, population of about 20,000, has been an agribusiness center, but with the construction of the U.S. Department of Energy's Supercollider the economy is changing.

Agricultural Activities

Historically, agriculture has been extremely important in the study unit. Land-use information for 1973-84 showed that about 11,700 mi2 or about 63 percent of the study unit was cropland or pasture or rangeland (U.S. Geological Survey, 1990). Recent (Texas Agricultural Statistics Service,1989) information shows that agricultural activities continue to be an important revenue source. The percentage of county area planted in a particular crop or crops in 1989 is shown on figure 11. The major crop category (fig. 11A) includes corn, cotton, peanuts, sorghum, soybeans, rice, and wheat. The percentage of county area planted in wheat (fig. 11B), rice (fig. 11C), and cotton (fig. 11D), are shown separately because of the significant differences in the management practices of these crops. Wheat and cotton are dry cropland crops and rice is an irrigated crop. Cotton commonly is subjected to more extensive (than other dryland crops) chemical treatments including pesticides and defoliants. Wheat commonly is treated with pre-emergent herbicides which may include trifluralin, bensulide, or dinoseb.

FIGURE 11.--Percent of county area planted in (A) major crops, (B) wheat, (C) rice, and (D) cotton.

Water Use

The current pattern of water use is not expected to change substantially over the next 50 years, with municipal use remaining the study unit’s major demand. Surface water is the main source of water supply for the study unit, and is predicted to remain so in the future (Texas Water Development Board, 1990). Total water withdrawals for 1990 were 3,164,000 acre-ft, and of that amount, an estimated 418,000 acre-ft or about 13 percent was consumptive. Surface-water withdrawals in 1990 were estimated to be 2,920,000 acre-ft with the remaining 123,000 acre-ft coming from ground water (Dee Lurry, U.S. Geological Survey, written commun., 1992).

Water use in the Trinity River Basin is divided into eight categories (table 3). The largest consumptive use is domestic with the majority being used in Dallas and Tarrant Counties because of their large populations. Transfers of water, from the adjoining basins and from reservoirs below Dallas and Fort Worth, are required to meet the needs of the metroplex. In 1989, a total of 89,700 acre-ft of water was transferred into the Trinity River Basin from the adjacent basins.

The largest category of withdrawals in 1990 was power generation with an estimated total of 2,000,000 acre-ft (table 3); however, of that, only about 1.2 percent was estimated to be consumptive use. Water use for mining purposes was concentrated on nonmetals, particularly in Wise, Dallas, and Liberty Counties. Manufacturing is widespread within the basin; however, most of these industries do not require large quantities of water per unit of product (Texas Department of Water Resources, 1984).

TABLE 3.--Water use in the Trinity River Basin study unit.

Irrigation activities predominantly occur in the rice-producing coastal area of the basin. Most of this water is supplied by surface water with some ground water pumped mainly from the Gulf Coast aquifer (Texas Department of Water Resources, 1984). Withdrawals for irrigation totaled 150,000 acre-ft in 1990 with an estimated 68,500 acre-ft of consumptive use. Livestock water use in the Trinity River Basin totaled 23,000 acre-ft in 1990.

Exports of water from the Trinity River Basin in 1989 totaled 287,000 acre-ft. The majority of the exported water was from the Trinity River downstream from Livingston Reservoir (Texas Water Development Board, 1990b).

Land Use and Land Cover

A land-use and land-cover classification, as documented by Anderson and others (1976), has been applied to the Trinity River Basin study unit. This information is a compilation of data from different dates so that some local anomalies exist in the basin description; however, the distribution of land use and land cover classes gives a good general indication for 1973 to 1981. The land-use and land-cover information was interpreted from topographic maps and high altitude aerial photos, and the final boundaries were compiled at a scale of 1:250,000 and digitized at that scale. The data are made available as Geographic Information and Retrieval System (GIRAS) files, and the entire United States has been mapped using this methodology (U.S. Geological Survey, 1990). The land-use and land-cover classification system, hierarchical in design, uses both a level 1 and level 2 classification. The level 1 classification, for example, "Agricultural Land", has been subdivided into "Cropland and Pasture" depending on the needs of the study. The distribution of selected classes from the land use and land cover classification for the study unit is summarized below and shown on figure 12.

- Forest Land and Wetlands - About 4,652 mi2 (25 percent) of the study unit was classified as forest land or wetlands (fig. 12A).
- Rangeland - about 1,781mi2 (10 percent) of the study unit was classified as rangeland (fig. 12B).
- Urban or Built up Land - about 1,011 mi2 (5 percent) of the study unit was classified urban (fig. 12C).
- Cropland and Pasture - about 10,513 mi2 (57 percent) of the study unit was classified as agricultural land, as cropland and pasture (fig. 12D).
- The remaining 613 mi2 (about 3 percent) of the study unit was classified as either open water or barren land.

FIGURE 12.--Land use and land cover classification for the study unit, 1973-81; (A) Forest Land and Wetlands, (B) Rangeland, (C) Urban or Built-Up Land, and (D) Cropland and Pasture.

IMPLICATIONS FOR WATER QUALITY

Solutes contained in natural water represent the net effect of a number of chemical reactions that dissolved material from another phase, altered previously dissolved components, or eliminated them from solution by precipitation or other processes. For these chemical processes to operate, there must be a means for supplying water and the other reaction components. The effectiveness of the chemical processes is influenced by numerous environmental factors (Hem, 1985). Climate is an important environmental factor, including the amount and rate of rainfall, runoff, and evaporation, and the temperature. The processes of rock weathering are strongly influenced by temperature and the amount and distribution of precipitation. The supply of naturally occurring solid reactants is ultimately controlled by geologic processes; elements not available in the rocks cannot be expected to be present in solution. The influence of climate goes beyond supplying water and acting as an agent for weathering. Climatic patterns tend to produce characteristic types of vegetation and soils which also influence water quality. Climate, soils, and topography influence human development. In some areas human activities are the dominant factor influencing water quality. Water-movement rates and solute-circulation rates may be altered by water diversions and reservoirs and by structures and paved surfaces that replace open land as cities expand. The ecology of large drainage areas can be altered as grasslands and forested lands are brought into cultivation. Solutes may be added to water by runoff from urban and agricultural lands, or directly by disposal of wastes.

Major Ions

In areas where human influences are small, concentrations and ratios of major ions in surface water are governed predominantly by the availability of minerals and the chemical composition and physical structure of the rocks and soils traversed by the water. The availability of minerals in soil is decreased by leaching. Readily-soluble minerals are leached by rainfall and, therefore, dissolved-solids concentrations from natural weathering are expected to be larger in the drier northwest part of the Trinity River Basin and smaller in the more humid southeastern part. Human activities that affect major ions in the Trinity River Basin include reservoirs, interbasin diversions, discharge of effluents from urban and industrial sources, and discharge of brines from oil and gas production.

As with surface water, the concentrations and ratios of major ions in ground water are governed predominantly by the availability of minerals and the chemical composition and physical structure of the rocks traversed by the water. Other factors affecting the concentration of major ions are the residence time of the water in the aquifer, proximity to salt deposits, infiltration of brines from oil and gas production from the land surface, and interformational and borehole leakage of brines from adjacent formations.

Suspended Sediment

Sediment concentrations and loads vary seasonally and areally as a function of the characteristics of source materials (surficial geology), amount of runoff, rainfall intensity, erodibility of soils, slope of the land, vegetative cover, and land use. Where source materials are fine grained, for example siltstones and shales, suspended sediment will tend to be fine grained. Urban development, especially during the actual construction phase, and some agricultural practices can cause more erosion and larger sediment concentrations in streams than are present in streams draining undisturbed areas.

Bed Sediment

Physical characteristics of bed sediment vary depending on the characteristics of the stream and of source materials of sediment to the stream. Where stream velocities are small, deposition of fine materials can occur; where stream velocities are large, fine materials will be transported downstream and larger materials such as gravel and cobbles will predominate. Types and concentrations of chemical constituents present in bed sediments will vary depending on the sources of materials (primarily surficial geology) and interactions with the aqueous phase (chemical reactions and sorption that can add or remove constituents from the sediments).

Trace Elements

Dissolved trace element concentrations vary depending on the pH and Eh of the water and on sources of trace elements in the watershed or aquifer. Sources of trace elements are related to geology, agricultural practices, mining practices, and urban development. Trace element concentrations on suspended sediment also vary greatly and are predominantly related to the surficial geology of sediment source areas and to proximity to sources of trace element contamination. Suspended trace element concentrations vary with flow condition; runoff can transport sediments from source areas into streams and, at larger flows, bed sediments can be remobilized which can move contaminants into the water column.

Nutrients

Nitrogen and phosphorus are essential nutrients for plant growth. Nitrogen (N) is derived naturally by the conversion of N2 gas to chemical compounds containing nitrogen, a process known as nitrogen fixation; phosphorus is mostly derived from weathering of rocks and sediments. Transport into streams can occur in the dissolved and suspended phases; therefore, concentrations are often related to suspended-sediment concentrations. Nutrient concentrations in streams are small in relatively undisturbed areas (Bass and Harrel, 1981). Variations in nutrient concentrations in the Trinity River Basin are predominantly the result of a variety of human activities including the discharge of treated municipal wastewater, construction of reservoirs, agriculture, and urban development.

Dissolved Oxygen and Biochemical Oxygen Demand

Aquatic biota require oxygen for metabolic processes. The equilibrium concentration of dissolved oxygen (DO) in water in contact with air is a function of temperature and pressure, and to a lesser degree, of the concentration of other solutes. The DO concentration may be depleted by processes that consume dissolved, suspended, or precipitated organic matter, and by metabolic processes in highly eutrophic systems, with values above equilibrium produced in systems characterized by high primary productivity (Hem, 1985). The biochemical oxygen demand (BOD) is the measured biochemical depletion of oxygen in a sample under controlled conditions (usually 5 days at 20 oC). It is considered a useful way of expressing stream-pollution loads. DO and BOD are important properties for describing water quality in the Trinity River because wastewater discharges containing large concentrations of BOD in the metroplex have led to smaller concentrations of DO downstream.

Synthetic Organic Compounds

By 1983, the American Chemical Society's Chemical Abstracts Service had registered over 4 million chemical compounds, most of which are synthetic organic compounds (Manahan, 1990). Environmentally-important groups of these compounds include pesticides, phenols, and polychlorinated biphenyls (PCB's). These compounds enter surface- and ground-water systems in point-source discharges, nonpoint-source runoff, and atmospheric deposition. Once in the water, their fate and distribution are affected by several processes including sorption interactions with sediments, bioaccumulation, and transformation processes. Transformation processes, including photolysis, hydrolysis, biodegradation, and volatilization, attenuate the concentration of an organic compound in solution (Smith, Witkowski, and Fusillo, 1988).

The occurrence of synthetic organic compounds is related to land use. The occurrence of different types of compounds are associated with different activities in the upstream watershed. For example, pesticides are associated with urban and agricultural usage (generally nonpoint sources) and PCB's are associated with industrial usage (generally point sources in urban areas). Spatial and temporal variations in concentrations occur as a result of proximity to sources, reservoirs, and changing regulations and user preferences for particular compounds.

Biota

The Trinity River supports diverse fish and benthic invertebrate fauna in some reaches. Fish communities at 8 out of 10 sites rated "exceptional" or "high" in an ecological study of the Trinity River using the Index of Biotic Integrity and aquatic-life use subcategories defined by the Texas Parks and Wildlife (Dickson, and others, 1989; Dickerson, and others, 1990). Density and species richness of macrozoobenthos vary throughout the study unit, and are influenced by such factors as substrate type, habitat heterogeneity, primary energy source, water temperature, and dissolved oxygen. Macroinvertebrate densities and taxa richness were consistently greater at relatively undisturbed sites, and were markedly less at sites immediately below several large regional wastewater-treatment facilities (Dickson and others, 1990). Organic pollution generally reduces taxa richness (Hynes, 1960), but may increase the total biomass and number of individuals in response to increased food supplies and inorganic nutrient levels. Heavy metals have been shown to reduce the relative abundance and species richness of aquatic macroinvertebrates (Eyres and Pugh-Thomas, 1978).

SUMMARY

The Trinity River Basin study unit extends approximately 360 mi to the north-northwest from its mouth at the Gulf of Mexico. Average annual precipitation varies from greater than 52 in. near the mouth to less than 36 in. in the northwest extreme. The variation in precipitation, combined with variations in temperature and surficial geology, has led to variations in landform, soils, and vegetation from southeast to northwest. Unique combinations of these factors have been used to subdivide the study unit into relatively homogeneous regions with respect to water quality.

Total population of the basin was about 4.5 million in 1990. Human modifications to the landscape and hydrologic system have been extensive. The natural environment of the basin has been altered by the development of livestock operations, the cultivation of large areas of the study unit, development of urban areas, discharge of wastewater, construction of reservoirs and energy resource development. During 1973-81, about 57 percent of the study unit area was pasture or cropland. An additional 10 percent was rangeland and 5 percent was urban or built-up land. Forest land, wetlands, open water, or barren land made up the remaining 28 percent. Twenty-two large and about 1,000 small reservoirs have been constructed on streams in the basin and numerous diversions carry water within the basin and to and from adjacent basins.

Water quality in the basin is affected by natural conditions and by human activities. Their relative importance, where known, varies for different water-quality properties and constituents; however, human development affects all eight categories of water quality presented in this report. The most significant water-quality issues can be attributed to the discharge of sewage effluent in the major urban areas.

REFERENCES SELECTED

A.H. Belo Corp.,1991, 1992-1993 Texas almanac (56th ed.): The Dallas Morning News, 656 p.

Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Baker, Bernard, Duffin, Gail, Flores, Robert, and Lynch, Tad, 1990, Evaluation of water resources in part of north-central Texas: Texas Water Development Board 318, 67 p.

Bass, David, and Harrel, R.C., 1981, Water quality of a southeast Texas stream: Hydrobiologia, v. 76, p. 69-79.

Brush, Samuel, and Promise, John, 1990, Influence of wastewater discharge on Trinity River water quality, in Jensen, Ric, ed., How healthy is the upper Trinity River--Proceedings of the Symposium on the Biological and Water Quality Perspectives of the Trinity River, October 2, 1990: Fort Worth, Texas Water Resources Institute, p. 13-45.

Carr, J.T., 1967, The climate and physiography of Texas: Texas Water Development Board Report 53, p. 2-5.

Dickson, K.L., Waller, W.T., Kennedy, J.H., Arnold, W.R., Desmond, W.P., Dyer, S.D., Hall, J.F., Knight, J.T., Malas, D., Martinez, M.L., and Matzner, S.L., 1989, A water quality and ecological survey of the Trinity River: Denton, Texas, University of North Texas, Institute of Applied Sciences, Report to Dallas Water Utilities, 339 p.

Dickson, K.L., Waller, W.T., Kennedy, J.H., Arnold, R.W., and Hall, J.F., 1990, A water quality and ecological survey of the Trinity River, in Jensen, Ric, ed., How healthy is the upper Trinity River--Proceedings of the Symposium on the Biological and Water Quality Perspectives of the Trinity River, October 2, 1990: Fort Worth, Texas Water Resources Institute, p. 13-45.

Eyres, J.P., and M.A. Pugh-Thomas, 1978, Heavy metal pollution of the River Irwell (Lancashire, United Kingdom) demonstrated by analysis of substrate material and macroinvertebrate tissue: Environmental Pollution, v. 16, p. 129-136.

Fenneman, N.M., 1931, Physiography of the western United States: New York, McGraw-Hill, p. 55-58.

Fenneman, N.M., and Johnson, D.W., 1930, Physical divisions of the United States: Washington, D.C., U.S. Geological Survey, scale 1:7,000,000.

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951-80: U.S. Geological Survey Hydrologic Investigations Atlas, HA-710, 1 sheet, scale 1:7,500,000.

Gilbert, C.R., and Sauer, S.P., 1969, Hydrologic effects of floodwater retarding structures on Garza Little Elm Reservoir, Texas: U.S. Geological Survey Open-File Report, 126 p.

Godfrey, C.L., McKee, G.S., and Oakes, Henry (comps.), 1973, General soil map of Texas, pt. 2, Soils, formation, classification and use: College Station, Texas A&M University Systems, Texas Agricultural Experimental Station, scale 1:1,500,000.

Hem, J.D., 1985, Study and Interpretation of the Chemical Characteristics of Natural Water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hill, R.T., 1901, Geography and geology of the Black and Grand Prairies, Texas: U.S. Geological Survey Annual Report 21 (1899-1900), pt. 7, p. 59-68.

Hirsch, R.M., Alley, W.M., and Wilber, W.G., 1988, Concepts for a National Water Quality Assessment Program: U.S. Geological Survey Circular 1021, 42 p.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416-B, 19 p.

Hynes, H.B.N, 1960, The biology of polluted waters: Liverpool, England, Liverpool University Press, 202 p.

Iman, R.L., and Conover, J.W., 1983, A modern approach to statistics. New York, John Wiley, 497 p.

Kier, R.S., Garner, L.E., and Brown, L.F., Jr., 1977, Land resources of Texas: Austin, Texas, University of Texas, Bureau of Economic Geology, 42 p.

Land, L.F., Schroeder, E.E., and Hampton, B.B., 1982, Techniques for estimating the magnitude and frequency of floods in the Dallas-Fort Worth Metropolitan area, Texas: U.S. Geological Survey Water-Resources Investigations Report 82-18, 55 p.

Larkin, T.J., and Bomar, G.W., 1983, Climatic atlas of Texas: Texas Department of Water Resources LP 192, 151 p.

Leahy, P.P., Rosenshein, J.S., and Knopman, D.S., 1990, Implementation plan for the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 90-174, 10 p.

Manahan, S.E., 1990, Environmental chemistry, (4th ed.): New York, Lewis Publishers, 612 p.

Muller, D.A. and Price, R.D., 1979, Ground-water availability in Texas, estimates and projections through 2030: Texas Department of Water Resources, Report 238, 77 p.

Nordstrom, P.L., 1982, Occurrence, availability, and chemical quality of ground water in the Cretaceous aquifers of north-central Texas: Texas Water Development Board Report 269, p. 3-7.

Omernik, J.M., and Gallant, A.L., 1987, Ecoregions of the south-central United States: U.S. Environmental Protection Agency, scale 1:2,500,000.

Peckham, R.C., Souders, V.L., Dillard, J.W., and Baker, B.B., 1963, Reconnaissance investigation of the ground-water resources of the Trinity River Basin, Texas: Texas Water Commission Bulletin 6309, 100 p.

Pettijohn, R.A., Weiss, J.S., and Williamson, A.K., 1988, Distribution of dissolved-solids concentrations and temperature in ground water of the gulf coast aquifer systems, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4082, 5 sheets, scale 1:3,500,000.

Ryder, P.D., 1988, Hydrogeology and predevelopment flow in the Texas Gulf Coast aquifer systems: U.S. Geological Survey Water-Resources Investigations Report 87-4248, 109 p.

Smith, J.A., Witkowski, P.J. and Fusillo, T.V., 1988, Manmade organic compounds in the surface waters of the United States--A review of current understanding: U.S. Geological Survey Circular 1007, 92 p.

Texas Agricultural Statistics Service, 1989, Texas agricultural statistics: Austin, Texas, Texas Agricultural Statistics Service, 202 p.

Texas Board of Water Engineers, 1958, Texas water resources planning at the end of the year 1958 - A Progress Report to the 56th Legislature: Texas Board of Water Engineers, p. 10, 33.

Texas Department of Water Resources, 1984, Water for Texas, A comprehensive plan for the future: Texas Department of Water Resources Report GP-4-1, v. 2, pt. III, sec. 8, p. 3

Texas Water Development Board, 1990, Water for Texas--Today and tomorrow: Texas Water

Development Board Document GP-5-1, 176 p.

U.S. Department of Agriculture, Soil Conservation Service, 1979, Final environmental impact statement, Trinity River watershed: U.S. Department of Agriculture, (ADM)79-1-(F)-TX, 94 p.

U.S. Geological Survey, 1990, Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps: U.S. Geological Survey Geodata Users Guide 4, 33 p.